ADVANCES IN HELICOPTER ELECTRIC TAIL ROTOR DRIVE

K. Stickels, M. Brunetti, M. Barber, B. Manimala, P. Brinson, T. Roe, Leonardo Helicopters
P.H. Mellor, J.D. Booker, S.J. Williamson, J. Yon, University of Bristol, UK

ABSTRACT

A recent EU JTI Clean Sky funded programme investigated the feasibility of powering the tail rotor of an intermediate-class helicopter electrically. The initial research and development program concluded that it was possible to produce a fault-tolerant permanent magnet electrical machine drive that has the required power density and integrity potential, but many challenges remain to produce a practical implementation, and still further challenges exist to develop a system that assures success at the certification phase. Now that the JTI programme has concluded, this paper presents an update on the activity outlining the developmental and experimental test activities that have led to a full scale demonstrated on a static aircraft and attempts to identify future opportunities.

1 INTRODUCTION

The last ten years has witnessed considerable investment in electrical machine drives, in particular addressing their efficiency and power density. This renaissance has been driven primarily by the automotive and renewable energy generation sectors, as they comply with increasingly stringent environmental legislation on a local, and increasingly global scale. Of particular interest is the increasing use of permanent magnet machines, which have attained new levels of power density by the utilisation of rare earth magnets, and precise control enabled by solid-state high frequency power electronics.

The rotorcraft sector is also facing increased environmental legislation, along with increased safety expectations and pressure to lower operating costs. However, with its' relatively small production volumes, it is more difficult to generate the necessary investment in fundamental new technologies that can bring about the changes required. One approach to this problem is to review emerging technologies from other industrial sectors and decide which of those can be exploited in an aerospace environment, and what development activity is required in order to integrate them in a form that could be considered for certification.

An opportunity to study the validity of this approach was realised under the JTI Clean Sky Green Rotorcraft research programme called ELETAD. The ELETAD programme was a modelling, simulation and rig development activity that demonstrates how these new electrical machine concepts can be utilised to replace the mechanical tail rotor drive components on a conventional open tail rotor helicopter with a fault tolerant electrical machine of equivalent power.

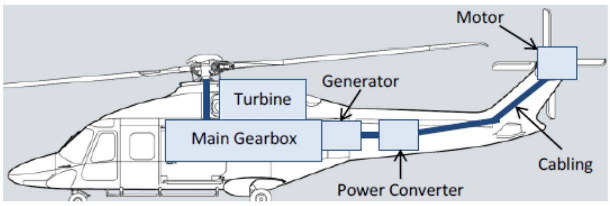

Figure 1. Electric tail rotor basic configuration

Such a system could have both environmental and operating advantages over a conventional mechanical tail drive.

- Fault tolerance by redundancy – conventional mechanical drives are simplex
- Elimination of toxic liquids (oil) and the overhead of maintaining it.
- Tail rotor no longer needs to be turning on the ground, saving fuel and reducing noise as well as increasing safety in, for example, an air ambulance role.
- Tail rotor speed need not be a fixed ratio of main rotor speed. It can be run at a slower speed or even stopped in forward flight, saving fuel, reducing noise and increasing life of components.

The ELETAD programme was executed by a consortium of academic and industrial partners led by the University of Bristol. The programme was overseen by Leonardo Helicopters UK as well as supplying the end user requirements and ensuring general aerospace applicability to the workflow.

The initial project objective was to capture the requirements of the existing tail rotor system and to derive from them the outline requirements for the electrical machine. These include:

- The nominal and transient power requirement;
- The rotational speed range over which the power needs to be developed;
- The amount of redundancy required to achieve the 10^{-9} failure rate;
- Outline environmental requirements;
- Constraints, eg size, electrical power input, properties of existing tail structure.

The initial phases of work entailed:

- Operational analysis to establish a target mission profile;
- Create a FMECA to establish the redundancy requirement;
- Carry out environmental testing on candidate winding topologies by forming motorettes. In particular, performing vibration and temperature cycling tests;
- Create software models of candidate machine topologies.

As work progressed it became clear that permanent magnet technology would be able to provide the greatest power in the most compact form factor. However it was unclear which of the two principal PM configurations – radial flux and axial flux – would provide the best overall solution. It was therefore decided that development should proceed with both configurations to the point of manufacturing a bench model that was electromagnetically representative. The final objective being to bench test both models on the electrical machine testing facility at the University of Bristol. This would enable the relative merits of each topology to be investigated, and also to refine the accuracy of the software models by comparing test data with the model prediction.

The findings up to this point were presented [1] at the 41st ERF in 2015, while the machine testing was still in progress. Unfortunately, the early machine prototypes suffered winding faults during testing. However, this situation enabled the development of improved specification and inspection methods for the winding manufacturing process. It also allowed the effects of a coil rewind on the machine performance to be studied. Furthermore, a novel method of detecting inter-strand short circuits within multi-stranded coils, prior to final winding, impregnation and termination, has been established.

Figure 2. Axial flux machine with dynamometer mounting arrangement at the University of Bristol

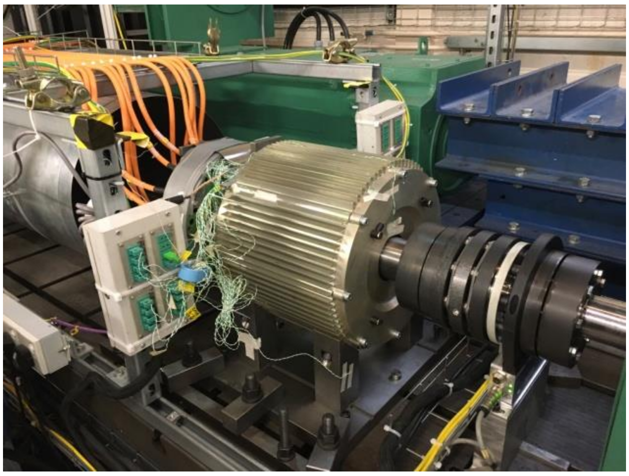

Figure 3. Radial flux machine undergoing dynamometer testing at the University of Bristol

Although both machine topologies have their advantages and disadvantages, the radial flux machine was selected for further development for the following reasons:

- The machine is physically more compact;

- The thermal paths from the stator coils to the exterior of the case are more direct and therefore cooling the machine becomes easier;
- The mechanical construction is less complex;
- There is less interaction or 'fight' between the isolated electrical sections as they share a common air gap in a radial machine and thus tend to have more equal characteristics.

2 SYSTEM DESIGN PHILOSOPHY

As mentioned earlier it was decided that the ELETAD programme, which concluded in 2015, had shown sufficiently promising results to warrant further development activity as a joint Leonardo Helicopters/University of Bristol collaboration in order to raise the TRL of the electric tail rotor (ETR) concept. The definition phase of this work encompassed the target rotorcraft, the mission profile and the system definition.

A decision was then taken as to which class of rotorcraft would most benefit from an electric tail rotor. The 'light' class (typically less than 4 tonnes MAUM) have very simple tail rotor transmissions, which require little power. The relative simplicity translates into low maintenance and inspection costs. Furthermore, the 'light' class is very price competitive, both on purchasing and operating costs, which make an electric tail drive difficult to justify at the current and medium-term projection of the available technology. By contrast the 'heavy' class (greater than 10 tonnes MAUM) have complex tail rotor transmissions with additional gearboxes and an intensive inspection and maintenance overhead which make it attractive to the concept of an electric tail rotor. However the size and weight of helicopters in this class means a correspondingly high continuous power rating is required. While this in itself is not a problem, it increases the complexity and cost of building a demonstrator, and also the risk if modifications are required. The 'intermediate' class (4 to 10 tonnes) retains the mechanical complexity of the 'heavy' class but with the benefit of a lower power requirement. The intermediate class of rotorcraft also finds itself cast into a number of varying roles – for example, SAR, maritime patrol, fisheries protection, air ambulance, simple point to point transportation and VIP duties. These roles all have a different power requirement for the tail rotor and mission analysis showed that rarely was it necessary to supply full power to the tail rotor. It is therefore possible to utilise a property of electrical machines - their ability to be intermittently rated – to design a lighter more compact tail rotor motor than would otherwise be possible. The AW139, a modern twin turbine rotorcraft of approximately 7 tonnes MAUM and in service with many operators in widely varying roles was considered an ideal target platform and the subsequent requirements definition phase was developed around the characteristics of this rotorcraft.

A useful property of electrical machines is their ability to be overdriven from their nominal rating for short periods, at the expense of their ultimate life. The nominal rating was determined by examining flight test data for varying missions to establish the mean power requirement and the spread of power demands.

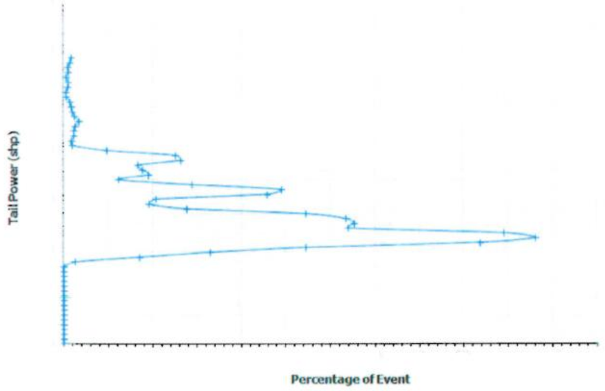

Figure 4. Example of flight test data output showing spread of tail rotor power requirements

From this and other data and requirements, a target set of requirements for the ETR machine was derived:

Fit, form and function compatible with AW139 TGB	
Quadruple electrical redundancy, 45 kVA nominal rating per section	
Weight of active materials	<50 kg
Nominal rotational speed	~1500 rpm
Nominal torque (continuous)	>1 kNm
Peak transient torque	>2 kNm
Electrical supply	115 V, 400 Hz 3-phase, 180 kVA (supply constraint)
Method of cooling	air

Table 1. Outline requirements for ETR machine

In order to contain this level of performance in a volume compatible with the AW139 tail rotor gearbox requires a specific torque capability of >20 Nm/kg, based on the weight of the active components. This is a challenging requirement for an air-cooled machine, but the University of Bristol's software models, already refined and validated from the ELETAD programme, predicted that it was an achievable goal.

So as to gain the maximum amount of knowledge from the programme, two rigs were designed. The first, located in Yeovil UK, is a dynamometer-style grooming rig using an electrical generator as a load feeding switchable resistive load banks. This rig is used to measure various parameters under controlled conditions.

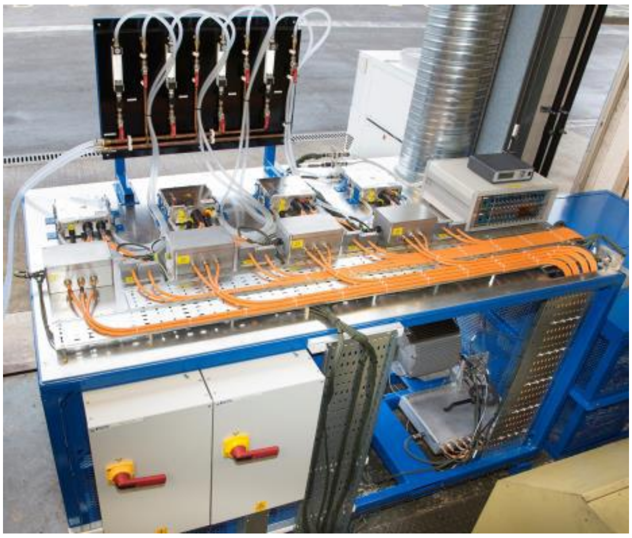

Figure 5. General view of UK grooming rig

The second rig, situated in Cascina Costa, Italy, is an 'Iron Bird' consisting of an AW139 tail cone on a space frame. On this rig, the ETR machine can be fitted with an AW139 hub, blades and pitch actuator, and can be tested with real dynamic loads created by the blade pitch. Furthermore, environmental effects can be assessed, in particular the airflow over the ETR machine created by the tail rotor.

Figure 6. General view of 'Iron Bird' rig

It was decided to continue with the quadruple electrical redundancy after the encouraging results with ELETAD. This necessitates an end-to-end isolation of the four electrical supply and control channels. This approach was constrained by the availability in the UK of 2 x 90 kVA electrical supplies. This was converted into 4 isolated 45 kVA supplies by the use of 4 phase shifting transformers and 18-pulse rectifier units.

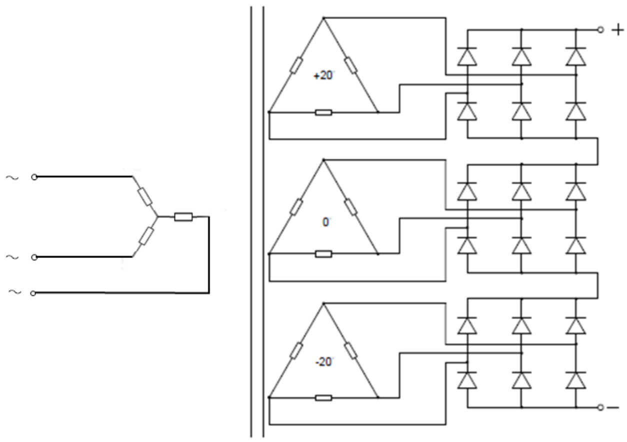

Figure 7. Schematic of phase shifting transformer/ 18-pulse rectifier unit

The advantage of this approach, besides creating four isolated supplies of 300 VDC output, is that both the ripple on the output and the distortion of the input caused by the non-linear rectifier load are much reduced, without the need for any extra correction devices. This supply arrangement was retained for the iron bird rig for these advantages even though 4 x 45 kVA supplies were available at the iron bird location.

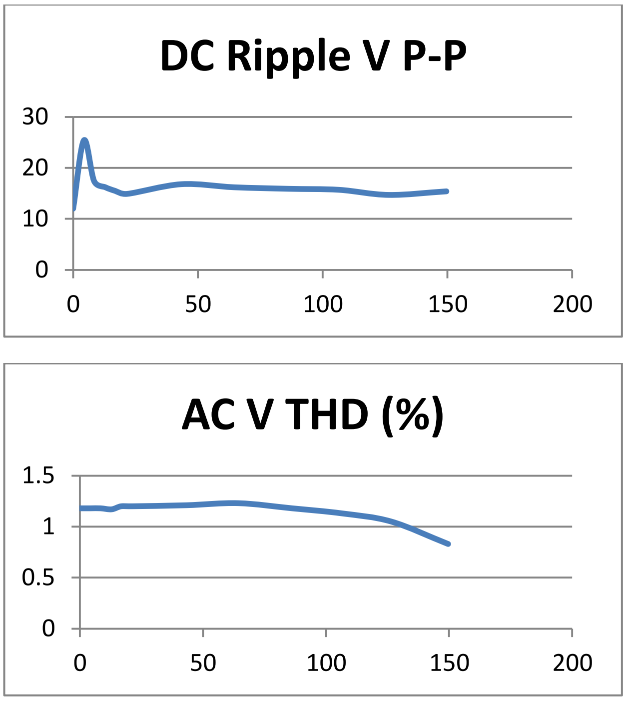

Figure 8. With transformer/18-pulse rectifier in circuit. Top: Ripple on DC output. Bottom: Distortion on input supply, plotted against current

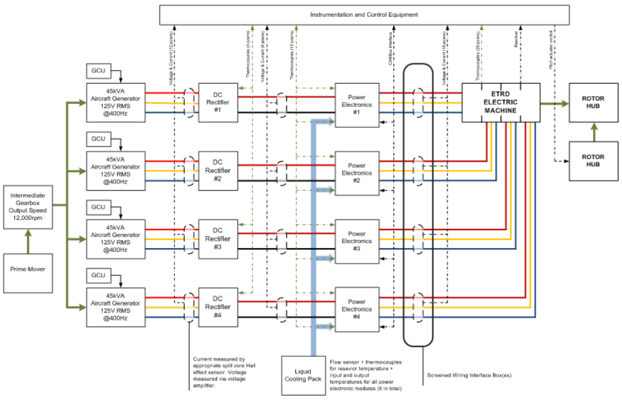

Figure 9. Block diagram of complete ETR electrical system showing the four isolated supplies

The final principal system components are the four PWM inverters. These units are sourced from the automotive sector and are nominally rated at 50 kVA each. Bespoke control software was embedded in firmware by the inverter supplier to match the characteristics of the ETR machine. This was done partly from design data supplied by the University of Bristol, and partly by characterisation on the supplier's dynamometer at their facility. The inverters are of a size and weight comparable with avionic equipment, and are built to similar standards as they are intended for use in high-end motorsport applications.

Figure 10. A 50kVA liquid cooled inverter

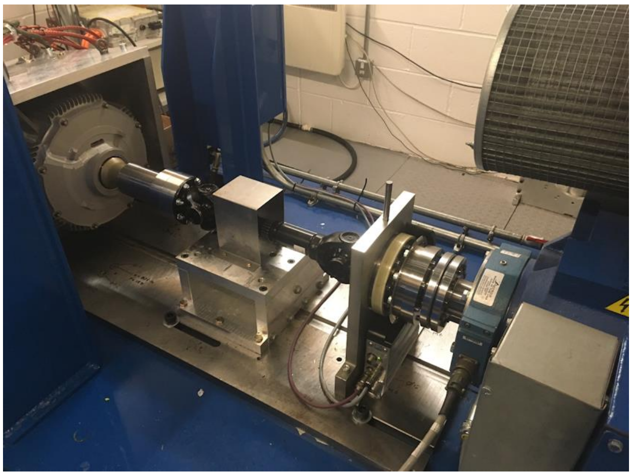

Figure 11. Characterising the ETR machine at the inverter supplier

3 ETR DESIGN PROCESS

Since the ETR machine was to interface with the AW139 tail rotor 'iron bird' in Italy, in addition to the requirements listed in Table1, the ETR had to be designed and manufactured to a quality equivalent to an aircraft part, and that the interface with the tail rotor hub and the pitch actuator were identical to the tail rotor gearbox. While it is not essential that the ETR follows the absolute profile of the TGB, care was taken to ensure that no fouling of moving parts could occur that could be caused by an alteration of dimensions. A workplan was therefore evolved with a clear 'division of labour' – the University of Bristol developed and evolved the ELETAD electromagnetic design, and Leonardo Helicopters concentrated on the mechanical design aspects, manufacture and assembly as well as the rig design and test plans. The following design aspects were given specific attention in order to address and refine issues found in the ELETAD design:

- Choice of stator lamination material and method of manufacture;
- Optimised calculation of interface between the stator and the casing to facilitate optimum thermal transfer [2];
- Choice of permanent magnet material and rotor lamination configuration;
- Optimisation of coil winding and slot design with particular attention to winding 'lay' consistency [3];
- Optimisation of slot liner insulation to provide maximum thermal transfer while retaining coil/stator insulation integrity [4];
- Taking into account the effect of bearing currents when using PWM inverters [5];
- Optimisation of coil winding and varnish impregnation manufacturing processes.

The improved software models due to data from the ELETAD testing phase were used to create reduced order thermal models, using a method described in the original ERF paper [1]. They were also used to study various combinations of slot liner, slot shape and coil fill factor to determine the best overall performance of the stator. These combinations were verified by manufacturing motorettes.

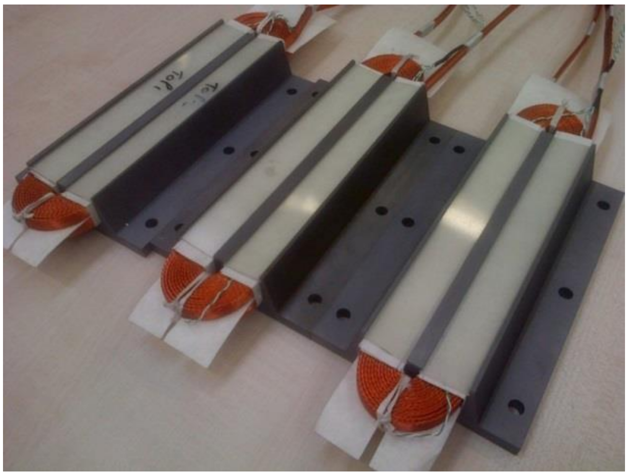

Figure 12. Motorettes before varnish impregnation

These are small sections of stator that contain one coil and slot liner, and are impregnated with varnish to be representative of a finished stator. They can be made at low cost and help to de-risk the stator design. By physically winding the wire around the stator the physical attributes of the coil can be verified, such as the end-turn overhang, the satisfactory fitment of the slot liner and comparison of measured electromagnetic characteristics with the model prediction. After varnish impregnation the motorettes were subjected to vibration and temperature endurance testing and the characteristics monitored for signs of insulation failure. This activity is particularly important given the unique environmental circumstances of rotorcraft compared to fixed wing aircraft (continuous vibration and no guarantee of cooling airflow due to forward airspeed). Endurance testing is by definition protracted but useful results have already been obtained and published [6] which will help to predict the ultimate life of the ETR machine windings.

The result of this activity resulted in a combination of rotor and stator configurations that possess a performance level superior to the ELETAD machines.

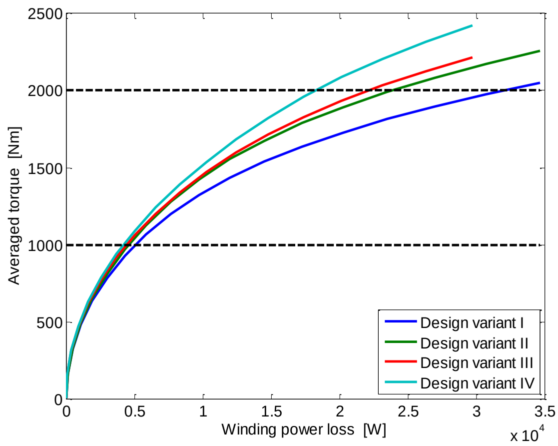

Figure 13. Iterative improvements in efficiency during ETR active component development

The mechanical design was undertaken by Leonardo Helicopters UK Transmissions Department, using the same 'vital part' workflow as a conventional tail rotor gearbox. The 'hard points' in the design are the tail fin/ETR machine interface and the pitch actuator mounting flange. Furthermore the position of the rotor hub was designed to be exactly in alignment with its position when fitted to the tail rotor gearbox. This is necessary to ensure the minimum of modifications to the AW139 'iron bird' rig, which has both practical consequences and allows easier signoff of the installation.

The design consists of a one-piece centre section into which the stator is inserted using a shrink-fit process. The one-piece rotor is retained within the centre section by front and rear end caps, into which grease filled bearings are inserted. The rear end cap has attachments for the fitment of the pitch actuator mechanism. The actuator rod can pass through the hollow rotor shaft in the same manner as the existing tail rotor gearbox.

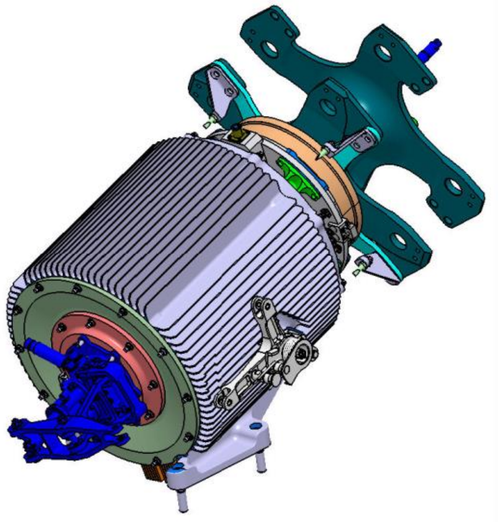

Figure 14. The final ETR machine design. The pitch actuator and tail rotor hub are shown fitted

Ceramic elements are used in one of the bearings to ensure that there are no circulating currents that could cause premature bearing failure by surface roughening [4]. Of particular concern is the maintenance of the correct air gap between the rotor and the stator under all flight loads as this has a profound effect on machine performance and in the final design the variation was proven to be insignificant.

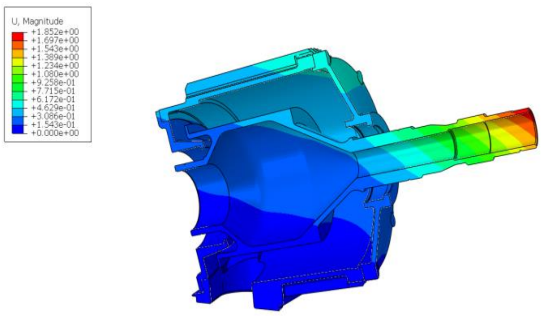

Figure 15. Analysis of stator/rotor air gap

A comprehensive structural analysis was undertaken on the ETR design using FE methods and actual AW139 flight loads data.

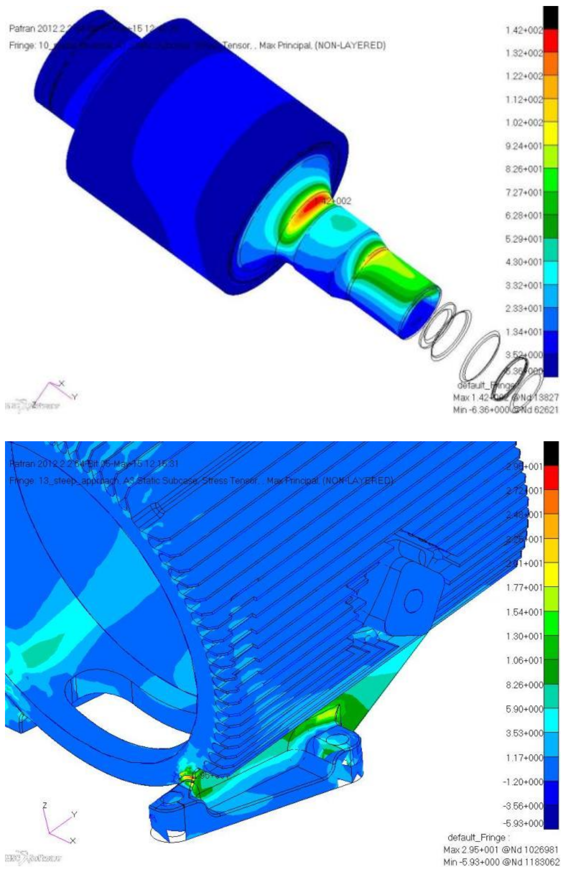

Figure 16. Examples of FE analysis output for the ETR rotor and centre section showing stress contours

4 MANUFACTURING AND ASSEMBLY

Like the design process, the manufacturing process utilised similar infrastructure and methods as those used to manufacture Leonardo Helicopters' tail rotor gearboxes. The casing parts and the rotor were machined from solid using 5-axis NC machines. Since the ETR machine was to be situated outside for the duration of the testing in Italy, the parts were subjected to the anti-corrosion treatment process used on the tail rotor gearbox components. The stator and rotor lamination stacks, which were cut using a wire EDM process, were assembled at the supplier's facility, were then located into their respective components. The coils were then assembled onto the stator and subsequently impregnated with varnish and cured. During the winding of the coils, temperature sensors were fitted at several locations within the stator assembly. The magnets were then assembled onto the rotor and retained with overbanding.

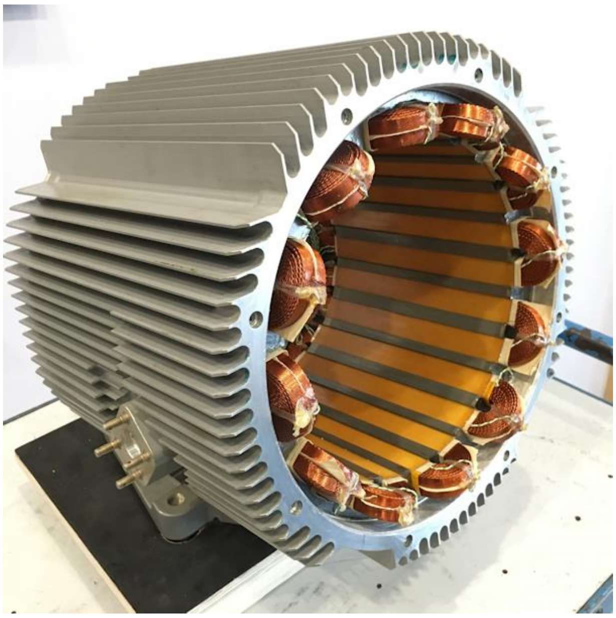

Figure 17. ETR centre section with completed stator

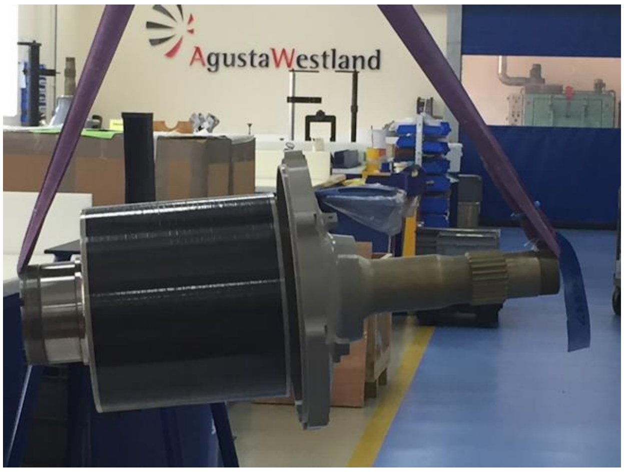

Figure 18. Completed rotor with front end cap fitted to rotor shaft

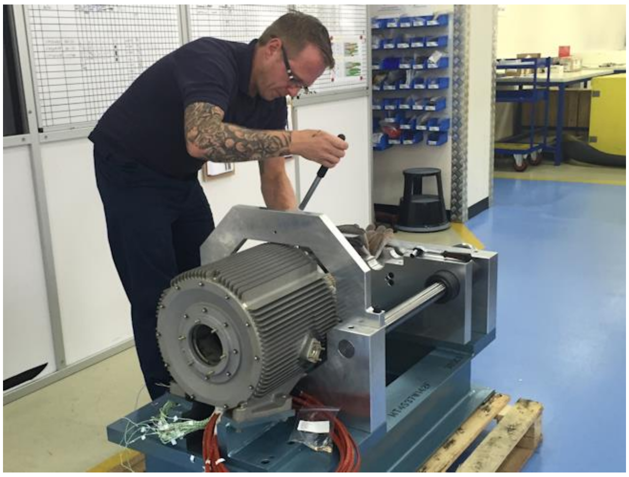

Figure 19. Final assembly in progress

With all the subassemblies complete the ETR machine was assembled using a jig to position the rotor centrally within the stator while the fasteners were tightened.

Sufficient parts to assemble three machines were manufactured. Two complete machines were assembled; the third was retained as a kit of parts that could be used to service failures with the other two as necessary. To date, no spare parts have been required.

5 DRIVE CONTROL ALGORITHM DEVELOPMENT

The development of a suitable control algorithm with which to test the ETR machine was a significant part of the rig development activity. Not only must it regulate accurately the speed of the ETR machine under normal operating conditions, but it must respond appropriately under abnormal and fault conditions to protect the surrounding environment and if possible, the machine itself. This was especially true on the 'iron bird' since actual AW139 tail rotor components were being used and their operating limits had to be respected.

To help ensure that all the requirements of the control system had been captured, a state diagram was constructed with all the possible fault conditions and operating modes included. The following MATLAB models were then constructed:

- AW139 tail rotor hub and blades;
- Grooming rig dynamic model;
- ETR machine model;
- Power inverters and electrical supply;
- The control algorithm itself.

As well as performing basic motor control, the control algorithm also contains functions such as motor stop/start and fault management. The models were ported to 3 PCs running the xPC RTOS, a very lightweight runtime environment and interconnected using CANbus. The models were used to develop the control algorithm by monitoring the behaviour of the ETR machine model under various stimuli such as steady state and transient loads. The latter case has particular significance on the iron bird, since the power inverters do not have a regeneration capability in this application, i.e. they cannot actively slow down the rotor. The effect of rotor overspeed caused by sudden reduction of blade pitch has to be accurately predicted to verify that the maximum permissible overspeed of the tail rotor hub is not exceeded.

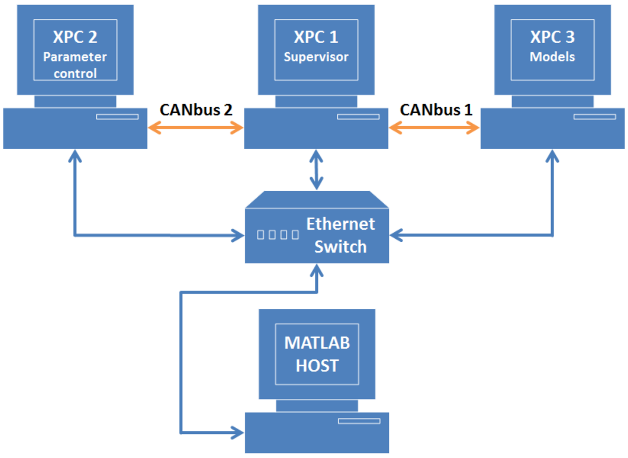

Figure 20. Control algorithm development environment. The MATLAB host and xPC 3 are not required when controlling the rig

Since the xPC RTOS does not support keyboard inputs, a number of selectable options are made available as part of parameter control at boot time. When the response from the models to the control algorithm was satisfactory, xPC machines 1 and 2 were integrated into the grooming rig.

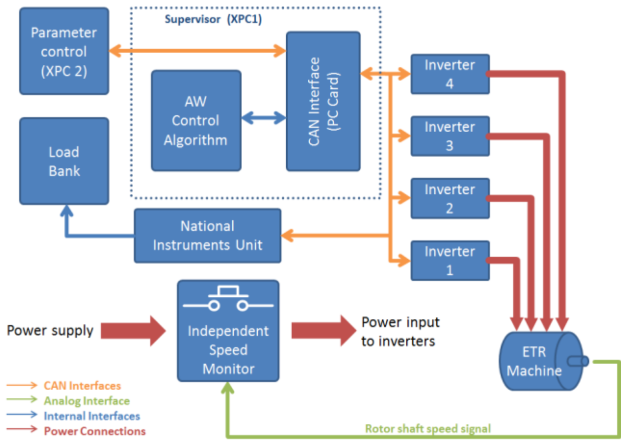

Figure 21. Control architecture of the grooming rig

On receiving a 'run at speed (x)' command from XPC 2, supervisor xPC 1 issues a torque demand to the power inverters via the CANbus. The inverters monitor the delivered torque to the ETR machine via the supplied current and acknowledge to the supervisor that this condition has been satisfied. They can do this because they have a firmware map of the machine characteristics. The inverters also 'self-resolve' the absolute rotor position by sensing back emf. Load bank switching is facilitated by a National Instruments PXI unit running an in-house developed LABVIEW program which also serves to log data from the ETR machine, inverters and the environment.

The case of a fault condition causing the ETR machine to run at a speed in excess of a safe maximum must be considered, since the high power developed by the machine could create a potentially hazardous situation. There are three levels of fault protection built into the rig architecture:

- The supervisor xPC unit outputs a torque demand of zero on detection of a fault code from an inverter, or an over temperature signal from the data logging software overriding any other command;
- The power inverters have a speed limit built into the firmware;
- The rig has an independent hardware implemented speed monitor fed from a separate tachogenerator mounted on the machine. This trips the supply to the inverters if the 'never-exceed' speed is reached.

In addition to the above, the rig operator has a manual 'bang button' with which they can operate *in-extremis* and electrically isolates the entire rig.

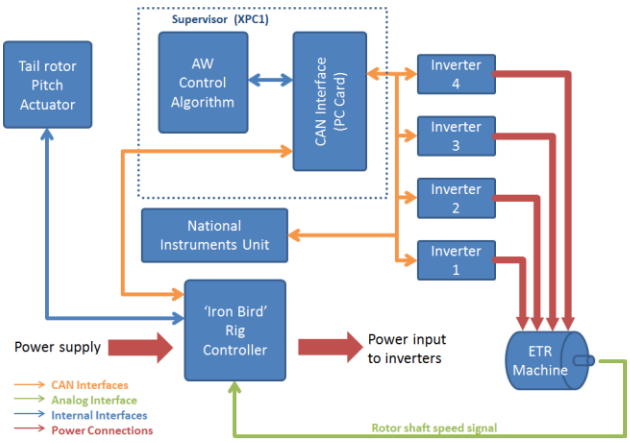

Figure 22. Control architecture of the Iron Bird rig

The control architecture of the Iron Bird rig is similar, but the rig infrastructure controller handles power supply isolation and parameter control. It also controls blade pitch, the equivalent of the load bank on the grooming rig. The PXI unit on the Iron Bird is performing a data logging function only.

Figure 23. Grooming rig control room. Rig operator at left, control algorithm development at right

Figure 24. Iron Bird control room. Supervisor display is at left and rig infrastructure display at right. The iron bird rig is visible through the control room window

6 GROOMING RIG TESTING

With the hardware containing the control algorithm integrated into the rig, the ETR machine was installed and coupled to the load machine.

Figure 25. ETR machine (right) coupled to load machine via a torque sensor on the grooming rig

During initial running it was found that further adjustments needed to be made to the power inverter firmware to get reliable start behaviour. With this done satisfactory steady state and transient behaviour was observed at speeds ranging from 800 to 1700 rpm. In addition a period of running was carried out at 1435 rpm, the nominal 100% rating of the AW139 tail rotor under a range of loading conditions.

Subsequent analysis of the results by the University of Bristol showed that the efficiency of the ETR machine was some 30% improved over the first prototype ELETAD radial flux machine, a pleasing result and validated the use of high performance magnetic materials and the revised winding arrangement. Furthermore, the machine characteristics were in good correlation with improved models constructed at the University of Bristol using the experimental results obtained from ELETAD.

With the ETR machine, the inverter firmware and the control algorithm software in a known serviceable condition, the iron bird rig was updated with the required changes and the ETR machine shipped to Italy for installation.

7 IRON BIRD TESTING

With the iron bird rig complete, the ETR machine was installed on the tail fin, along with the pitch actuator, tail rotor hub and blades, which are all standard AW139 components.

Figure 26. ETR machine installed on the tail fin of the iron bird, along with the pitch actuator and operating mechanism. A hub equivalent mass is fitted to the ETR shaft in preparation for resonance testing

Figure 27. Strain gauges were applied at strategic points on the tail cone

Figure 28. The completed installation

It was found that the installation of the ETR machine was completed much more quickly than that typically required for a mechanical tail rotor, as the need for critical shaft alignment and lubrication had been eliminated.

With the preliminary rig tests completed and the ETR installation checked and approved, the rig was fully commissioned at the end of 2016 with a series of steady state tests followed by loading tests created by changing the pitch of the blades. As observed on the grooming rig, once again a pleasing correlation to the predictions of the machine models was obtained.

The iron bird rig is situated outside, and variable weather conditions at the time of commissioning reduced the opportunity for extended testing, being alternately very cold and foggy, and then very wet. However it was possible to demonstrate the complete system to the Clean Sky JU, and a short video of this event is available to view [7].

Figure 29. The ETR machine running on the iron bird rig

8 DISCUSSION

The outcome of this programme to date has produced a most encouraging set of results. It has shown the value of a rigorous model-based approach, iteratively refined by the inclusion of test data. It has validated the radial flux permanent magnet machine concept as a viable package to deliver the power required for a helicopter of the size and mass of the AW139. A design and manufacture workflow has been established within the existing transmissions infrastructure within Leonardo Helicopters. Traditionally the policy of ‘vital part’ status for transmission components has ensured that the rotorcraft D & D authority has total control over the integrity of the part by supervising all aspects of design and manufacture, with only a small quantity of bought-in components such as fasteners and bearings – although even these are rigorously specified. For the purposes of the Clean Sky programme, a larger quantity of bought-out components have been specified, specifically the active electrical components such as laminations, coils and magnets. This was considered justifiable in a research contract for a non-flying part. It is unlikely that laminations and magnets would ever be manufactured in-house, but in a more-electric scenario where vital dynamic components are augmented or replaced by electric actuation, incorporation of electrical skills into traditionally a totally mechanical discipline will be required. During the ETR programme methods and tooling were developed to work with large lamination stacks, and it was found that these new processes were well within the skill set already available within Leonardo Helicopters.

It could be judged that TRL 5/6 has been reached within the ETR programme, but clearly much work remains to be done if an electric tail rotor is to become a credible alternative to existing mechanical systems. Although an end-to-end system has been demonstrated, some compromises have had to be made because of real-world constraints. Principally among these has been the use of existing aircraft generators which limits the available supply voltage to 300 VDC maximum. Consideration needs to be given to the efficient and reliable generation of the electrical power required for the electric tail rotor. Already in the automotive sector 540 VDC is being proposed for some applications, and this higher voltage could have advantages in an electric tail rotor application by reducing cable mass, but would need to be considered within the wider context of a high voltage supply requirement on aircraft generally, and the need for standardisation.

Another important consideration is the safety critical nature of the helicopter tail rotor. Even though the rotor itself is simplex, the mechanical implantation has benefitted from some 70 years of development and as a result become reliable and well understood – although the maintenance requirement, and thus cost to the operator – is high. An approach to satisfying concerns that an electrical system might not be as reliable is to create redundancy within the system, and is the approach taken with the ETR. Four totally electrically independent channels have been provided, and the same fault tolerance has been continued within the ETR machine itself. The approach ensures that an electrical failure in one channel does not affect the function of the others.

An aggressive programme of weight management is also required, both in the ETR machine itself and in the system generally. It was mentioned earlier that a useful property of electrical machines is their ability to be overdriven far in excess of their nominal design rating. A major consideration in the future test programme is to ascertain if the ETR machine has been conservatively or optimistically designed under static, transient and mission typical loadings, consistent with expected reliability, life and maintenance requirements. The ETR machine was sized using conventional tail rotor methods. These tests will help either to confirm that the existing methods are still valid, or whether a new approach is required. Either way, a straight substitution of a mechanical tail rotor for an electrical one is unlikely to be an optimum solution. An electric tail rotor has the potential to allow rotorcraft designers freedom to investigate alternative, rotorcraft concepts that have hitherto been impossible to realise.

9 REFERENCES

1) Mellor, P, Yon, J, Williamson, S, Farman, J, Booker, J, Barber, M, Stickels, K & Brinson, P, 2015, 'Electrical machine technologies for an electric tail rotor drive', Proceedings 41st European Rotorcraft Forum, 2015, Vol.2: pp. 1159-1166.
2) Booker, JD, Lock, RJ, Williamson, SJ & Gómez, JF, 2016, 'Effective practices for the concept design of electromechanical systems', Journal of Engineering, Design and Technology, vol 14., pp. 489-506.
3) Wrobel, R, Williamson SJ, Simpson, N, Ayat, S, Yon, J, & Mellor, PH, 2015, 'Impact of slot shape on loss and thermal behaviour of open-slot modular stator windings', IEEE Energy Conversion Congress and Exposition (ECCE 2015), pp 4433-4440.
4) Wrobel, R, Williamson, SJ, Booker, JD & Mellor, PH, 2016, 'Characterising the 'in situ' Thermal Behaviour of Selected Electrical Machine Insulation and Impregnation Materials', IEEE Transactions on Industry Applications, vol 52., pp. 4678-4687.
5) Erdman, J, Kerkman, RJ, Schlegel, D & Skibinski, G, 1995, 'Effect of PWM Inverters on AC Motor Bearing Currents and Shaft Voltages', IEEE APEC Conference, March 1995, Dallas, Texas, USA.
6) Williamson, S, Wrobel, R, Yon, J, Booker, J & Mellor, P, 2016, 'Effects of Insulation Ageing on the Conductive Heat Transfer from the Winding Body into Machine Periphery/Stator Core Pack', 8th IET International Conference on Power Electronics, Machines and Drives, 19 – 21 April, Glasgow, 2016.
7) https://www.youtube.com/watch?v=-LIH_6581QE

10 LIST OF ACRONYMS

AW	AgustaWestland
CAN	Controller Area Network
D&D	Design and Development
ELETAD	ELEctric TAil Drive (Clean Sky research programme)
EDM	Electrical Discharge Machining
ERF	European Rotorcraft Forum
ETR	Electric Tail Rotor
EU	European Union
FE	Finite Element (Model)
FMECA	Failure Modes, Effects & Criticality Analysis
GCU	Generator Control Unit
JTI	Joint Technology Initiative
JU	(Clean Sky) Joint Undertaking
MAUM	Maximum All Up Mass
NC	Numerically Controlled (machine tool)
PM	Permanent Magnet
P-P	Peak to Peak
PXI	PCI eXtensions for Instrumentation
PWM	Pulse Width Modulation
RMS	Root Mean Square
RTOS	Real Time Operating System
SAR	Search and Rescue
SHP	Shaft Horse Power
TGB	Tail Rotor Gear Box
THD	Total Harmonic Distortion
TRL	Technology Readiness Level

11 CONTACTS

Keith.Stickels@leonardocompany.com
Massimo.Brunetti@leonardocompany.com
P.H.Mellor@bristol.ac.uk
J.D.Booker@bristol.ac.uk